WIMP identification through a combined measurement of axial and scalar couplings

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We study the prospects for detecting Weakly Interacting Massive Particles (WIMPs), in a number of phenomenological scenarios, with a detector composed of a target simultaneously sensitive to both spin-dependent and spin-independent couplings, as is the case of COUPP (Chicagoland Observatory for Underground Particle Physics). First, we show that sensitivity to both couplings optimizes chances of initial WIMP detection. Second, we demonstrate that in case of detection, comparison of the signal on two complementary targets, such as in COUPP CF_3I and C_4F_{10} bubble chambers, allows a significantly more precise determination of the dark matter axial and scalar couplings. This strategy would provide crucial information on the nature of the WIMPs, and possibly allow discrimination between neutralino and Kaluza-Klein dark matter.

Introduction. A variety of astrophysical and cosmological observations provide convincing evidence that the matter budget of the Universe is dominated by *Dark Matter* (DM), made of some new, yet undiscovered, particles that interact weakly or less-than-weakly with those of the Standard Model (SM). The fact that some well-motivated extensions of the SM, such as Supersymmetry (SUSY) and theories with extra-dimensions, *naturally* provide excellent DM candidates, has attracted the interest of the particle physicists community, and many current and upcoming searches are planned to tackle the question of the nature and the properties of DM particles (for recent reviews, see, e.g., Refs. [1, 2, 3, 4]).

DM can be searched for *directly*, as DM particles passing through the Earth interact inside large detectors. The field of direct searches is well-established, with many experiments currently operating or planned. Direct detection relies on one of two modes of interaction with target nuclei. Scalar, or so-called *spin-independent*, coupling describes coherent interactions of DM with the entire nuclear mass. Axial, or so-called *spin-dependent*, coupling describes interaction of DM with the spin-content of the nucleus. Overall, more attention has been given to interpretation of direct detection results in terms of the scalar interaction, and most experimental efforts have focused on using heavy-nucleus targets which enhance the scalar-interaction scattering rate. However, as detailed below, it is generally not known whether first direct detection of DM particles is more likely to occur via scalar or axial interactions. Furthermore, determination of the nature of DM parameters will require quantification of both types of interaction by measurement of the scattering cross-section on multiple target nuclei. Finally, spin-dependent couplings are also of special interest since one of the most promising indirect searches aim at the detection of high energy neutrinos from DM annihilations at the center of the Sun, where DM would accumulate precisely due to spin-dependent interactions with the nuclei of the Sun.

In this letter we concentrate the discussion around a new experiment, COUPP (Chicagoland Observatory for Underground Particle Physics), which exploits an old technique, the bubble chamber, in the new context of direct dark matter detection [5]. We make a case study of it, given that the target liquid employed (CF_3I) has an extreme simultaneous sensitivity to spin-dependent-proton and spin-independent couplings, via the presence of fluorine [6] and iodine respectively. We compare expectations with other detectors not profiting from this high degree of simultaneous sensitivity, such as the case of Germanium-based searches. Another important distinguishing feature of COUPP is the ability to run modules containing C_3F_8 or C_4F_{10}, much more sensitive to the spin-dependent than -independent contributions to the signal rate. This multiplicity of targets can be exploited to identify the nature and properties of a WIMP. The conclusions are, however, not unique to COUPP and can be extended to argue the present need for a variety of targets and experiments, if a clear picture of the characteristics of a dark matter particle is to be obtained.

Detection Challenges and COUPP. In order to explore extensive regions of the DM parameter space, direct detection experiments must rise to the challenge of constructing ton-scale detectors with only a few background events per year. Even deep underground, where cosmic-ray backgrounds can be substantially reduced, naturally occurring radioactivity poses quite a challenge. COUPP (Chicagoland Observatory for Underground Particle Physics) uses stable room-temperature bubble chambers to search for DM particles scattering off of nuclei in superheated liquid. The superheated refrigerant initially used, CF_3I, is an inexpensive fire-extinguishing agent. CF_3I is an excellent WIMP-

detector: iodine is an optimal target for spin-independent (SI) interactions, fluorine is the best possible target for spin-dependent-proton (SD_p) interactions, and both iodine and fluorine are good targets for spin-dependent-neutron (SD_n) interactions. Because of COUPP's simplicity, room temperature operation and the low cost of several target liquids of interest, COUPP detectors are quite inexpensive as compared with other approaches to DM detection.

COUPP presently operates a 2 kg chamber at the 300 meters of water equivalent depth of the Fermilab neutrino tunnel. The potential reach of this CF_3I-filled chamber at the current depth is presented in [7]. Which sensitivity is actually achieved will depend on the level of alpha-emitter contamination in the detection volume (in contrast to most direct detection experiments, COUPP's demonstrated minimum ionizing background rejection of $> 10^{10}$ makes reduction of alpha-emitters its sole radiopurity concern [7]).

The short-term goals for COUPP are to reduce the alpha-recoil backgrounds in the 2kg chamber to a level of less than one event per kg per day, and to apply the upgrades tested on it to larger chambers currently under construction. The collaboration is constructing larger devices, totaling 80 kg of CF_3I. Long-term plans involve the deep-underground installation of a target mass of order one ton, using a number of different refrigerant targets for an exhaustive exploration of DM models. The ability of COUPP to use the same detector technology to measure interaction rates on a range of targets is considered to be one of the principal strengths of this approach.

Theoretical Predictions. In SUSY extensions of the SM a discrete symmetry, known as R-parity, is often imposed in order to forbid lepton and baryon violating processes which could lead, for instance, to proton decay. A phenomenological implication of this is that SUSY particles are only produced or destroyed in pairs, thus rendering the lightest SUSY particle (LSP) stable. Remarkably, in large areas of the parameter space of SUSY models, the LSP is an electrically neutral particle, the lightest neutralino, $\tilde{\chi}_1^0$, which therefore constitutes a very well motivated DM candidate, within the class of WIMPs [1, 3].

The neutralino is a linear superposition of the fermionic partners of the neutral electroweak gauge bosons (bino and wino) and of the neutral Higgs bosons (Higgsinos), and the resulting detection cross section is extremely dependent on its specific composition. The scalar part of the neutralino-proton cross section, σ_p^{SI}, receives contributions from Higgs exchange in a t-channel and squark exchange in an s-channel. The latter also contributes to the spin-dependent part of the cross section, σ_p^{SD}, together with a Z boson exchange in a t-channel. The expressions for the different amplitudes can be found, e.g., in [8]. Thus, a large Higgsino component induces an enhancement of both the Higgs and Z boson exchange diagrams, thereby leading to an in-

crease in both the spin-dependent and -independent cross sections. On the other hand, the presence of very light squarks leads to an enhancement of (mainly) σ_p^{SD}.

In order to determine the theoretical predictions for the neutralino detection cross section we have performed a random scan in the effective MSSM (effMSSM) scenario, where input quantities are defined at the electroweak scale [9]. The mass parameters have been taken in the range $0 \leq \mu$, m_A, M_1, $m \leq 2$ TeV with $3 \leq \tan\beta \leq 50$, and $-4\,M_1 < A < 4\,M_1$ (see [8, 10] for a similar scan). A small non-universality in squark soft masses has also been included, taking $m_{Q,u,d}^2 = (1 \ldots 5)\,m^2$. The results are depicted in Fig. 1a) by means of empty circles. Noteworthy, regions with large σ_p^{SD} are obtained, some of which predict a small σ_p^{SI}. In a second scan we have studied supergravity-inspired models in which the soft terms are inputs at the grand unification scale. We have considered the most general situation, with non-universal scalar and gaugino masses, exploring the scenarios presented in [12] for $3 \leq \tan\beta \leq 50$ (see for comparison [13], where the scenario with universal parameters is studied). The results are shown in Fig. 1a) with gray dots. In this case a simultaneous increase in both σ_p^{SD} and σ_p^{SI} is observed. We leave the details of these scans and the implications on the SUSY parameter space for a forthcoming work. These results strongly suggest the need of combining spin-dependent and -independent techniques in order to effectively explore the whole SUSY parameter space.

Although theoretically very well motivated, SUSY is not the only possible extension of the SM leading to a viable DM candidate. An interesting alternative arises in theories with Universal Extra Dimensions (UED), in which all fields are allowed to propagate in the bulk [14]. In this case, the Lightest Kaluza-Klein Particle (LKP) is a viable DM candidate, likely to be associated with the first KK excitation of the hypercharge gauge boson [15, 16], usually referred to as $B^{(1)}$. In absence of spectral degeneracies, the $B^{(1)}$ would achieve the appropriate relic density for masses in the 850–900 GeV range [15]. However, due to the quasi-degenerate nature of the KK spectrum, this range can be significantly modified, due to coannihilations with first [20, 21] and second [22, 23, 24] KK-level modes. The allowed mass range was also found to depend significantly on the mass of the Standard Model Higgs boson [22], and in general on the matching contributions to the brane-localized kinetic terms at the cut-off scale (see the discussion in Ref. [20]).

Our calculation of the LKP scattering cross section off nucleons closely follows [17] (see also [15]). In practice, it is performed in a way very similar to the case of SUSY, evaluating the amplitudes for scattering of the $B^{(1)}$ particles off nucleons. In UED the leading contribution comes from the exchange of the Higgs (for scalar coupling) and of first level KK quarks $q^{(1)}$ (for both axial and scalar couplings). We will work under the usual assumption that all first level KK quarks are degenerate with mass
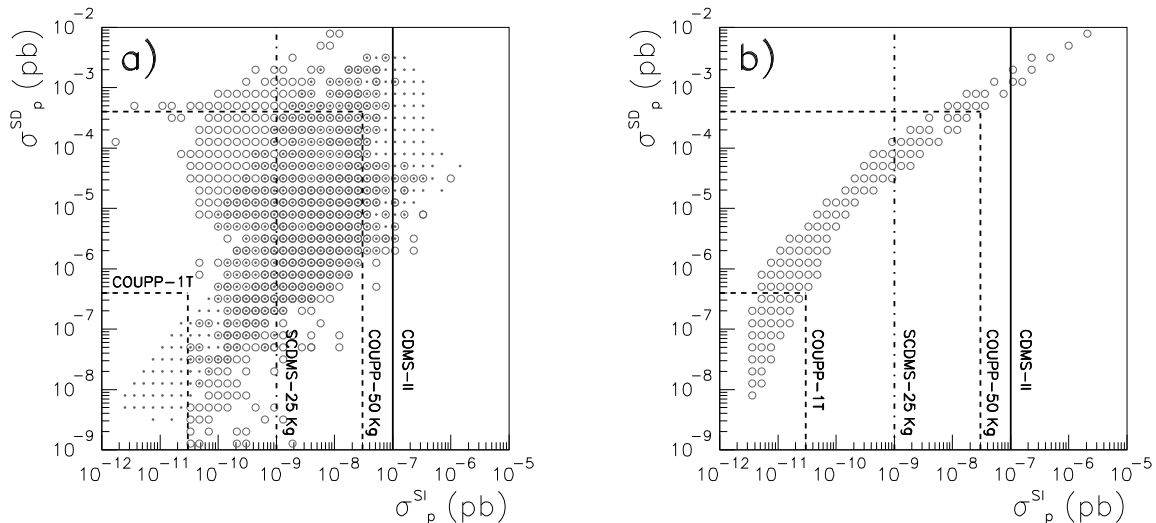
FIG. 1: Theoretical predictions for σ_p^{SD} versus σ_p^{SI} obtained from a set of random scans in the various supersymmetric (effMSSM and supergravity-inspired) scenarios (left) and in the UED scenario (right). All the points fulfil existing experimental constraints and reproduce the correct dark matter relic density. The current and projected sensitivities of the CDMS detector (25 kg stage) are also represented with solid and dot-dashed lines, respectively, together with the potential reach of COUPP (dashed lines). The sensitivity of COUPP at 1 ton target mass is based on the goal of matching the lowest alpha-emitter concentrations so far achieved in neutrino experiments [7] (e.g., KAMLAND [11]).

$m_{q^{(1)}}$. The resulting spin-dependent and -independent LKP detection cross section is represented in Fig. 1b), where (in view of the aforementioned theoretical uncertainties on the $B^{(1)}$ parameters) we took a rather liberal approach, and let the $B^{(1)}$ mass $m_{B^{(1)}}$, and the normalized mass difference between the first level KK quarks and the $B^{(1)}$, $R_{q^{(1)}} \equiv (m_{B^{(1)}} - m_{q^{(1)}})/m_{B^{(1)}}$, to vary independently in the range 300 GeV $\leq m_{B^{(1)}} \leq$ 2000 GeV, and $0.01 \leq R_{q^{(1)}} \leq 0.5$. Note that masses $m_{B^{(1)}} \lesssim 300$ GeV are excluded by electroweak precision data [25, 26]. As one can see, LKP models tend to populate a different region of the parameter space with respect to SUSY scenarios, due to the larger spin-dependent cross-section.

WIMP Discovery and Identification. The discovery of neutralino DM might take place through either scalar or axial coupling. In contrast, discovery of LKP DM is for most, but not all, models expected to occur through axial coupling. The ability of COUPP to run with a target such as CF$_3$I, which has optimal SI, SD$_n$, and SD$_p$ couplings, is an advantage of this experiment in the race for first detection. Supposing an experiment succeeds in directly detecting DM particles, it is interesting to consider how the nature of the DM (e.g. neutralino or LKP) might be determined. The possibility of running with a range of detection fluids makes COUPP well-poised to determine the nature of DM upon successful detection. As shown in Fig. 2(a), measurement of an event rate in a single detector does reduce allowed models, but does not generally place significant constraints on coupling parameters or on the nature of detected DM (i.e. neutralino or LKP). However, as shown in Fig. 2b), subsequent detec-

tion of an event rate on a second target does substantially reduce the allowed range of coupling parameters, and allows, in most cases, an effective discrimination between neutralino and LKP DM (it has recently been pointed out [27] that a combination of direct and indirect detection techniques might also help distinguishing between these two candidates). The combination of detector fluids used in Fig. 2 is effective in reducing the allowed range of $\sigma_p^{\mathrm{SI}}/\sigma_p^{\mathrm{SD}}$ because massive iodine nuclei have a large SI coupling, while fluorine nuclei have a large SD$_p$ coupling. It must be noted that fluorine and iodine have very similar neutron cross sections. Monte Carlo simulations show that CF$_3$I and C$_3$F$_8$ or C$_4$F$_{10}$ exhibit essentially the same response to any residual neutron background, i.e., neutrons cannot mimic an observed behavior such as that described in the discussion of Fig. 2. Other combinations of targets such as germanium and silicon are more prone to systematic effects where residual neutron recoils can mimic the response expected from a WIMP with dominant spin-independent couplings.

Conclusions. As we have shown with Fig. 1, in certain phenomenological scenarios a detector sensitive exclusively to one mode of interaction may lack sensitivity to a large fraction of WIMP candidates. The possibility of operating experiments, such as COUPP, with a range of detection fluids, makes them ideally suited to determine the nature of dark matter upon successful detection, i.e., to distinguish between LKP and neutralino candidates, and in the second case, to pinpoint the properties of the particle in an otherwise vast supersymmetric parameter space. The arguments presented here for the case study
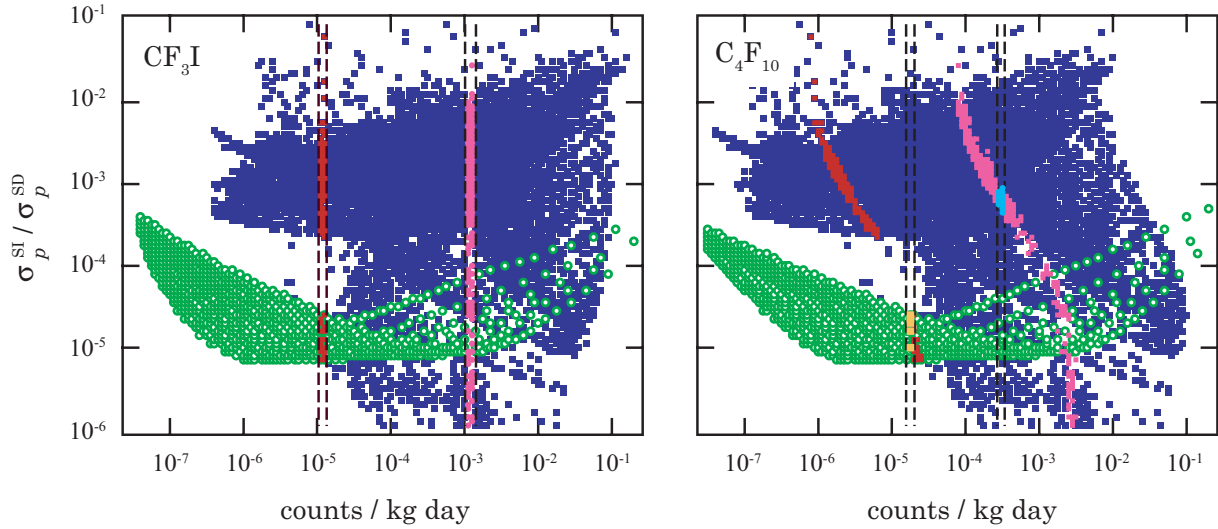
FIG. 2: *Left Panel:* The detection of a DM signal with a CF_3I detector can only loosely constrain DM candidates (blue squares for neutralinos, green circles for the LKP) in the $\sigma_p^{SI}/\sigma_p^{SD}$ versus count-rate plane. Red (magenta) dots show the many models consistent with a measurement of $\sim 10^{-5}$ (10^{-3}) counts / kg day on CF_3I. *Right Panel:* measurement of the event rate in a second detection fluid such as C_4F_{10}, with lower sensitivity to spin-independent couplings, effectively reduces the remaining number of allowed models–orange (aqua) dots–and generally allows discrimination between the neutralino and the LKP (a 10% uncertainty in the measurements is adopted here for illustration).

of COUPP can be easily generalized to a combination of data from experiments using targets maximally sensitive to different couplings, supporting the tenet that a large variety of DM detection methods is presently desirable.

[1] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267** (1996) 195 [arXiv:hep-ph/9506380].

[2] L. Bergstrom, Rept. Prog. Phys. **63** (2000) 793 [arXiv:hep-ph/0002126].

[3] C. Muñoz, Int. J. Mod. Phys. **A19** (2004) 2093 [arXiv:hep-ph/0309346].

[4] G. Bertone, D. Hooper and J. Silk, Phys. Rept. **405** (2005) 279 [arXiv:hep-ph/0404175].

[5] W. J. Bolte et. al., Nucl. Instr. Meth. A, in press, [arXiv:astro-ph/0503398].

[6] J. Ellis and R. A. Flores, Phys. Lett. B **263(2)** (1991) 259 [arXiv:hep-ph/9612376].

[7] E. Behnke *et al.*, in preparation; http://www-coupp.fnal.gov/

[8] J. R. Ellis, A. Ferstl and K. A. Olive, Phys. Lett. **B481** (2000) 304 [arXiv:hep-ph/0001005]; J. R. Ellis, A. Ferstl and K. A. Olive, Phys. Rev. D **63** (2001) 065016

[arXiv:hep-ph/0007113].

[9] L. Bergstrom and P. Gondolo, Astropart. Phys. **5**, 263 (1996) [arXiv:hep-ph/9510252]; A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Lett. B **423**, 109 (1998) [arXiv:hep-ph/9709292].

[10] V. A. Bednyakov and H. V. Klapdor-Kleingrothaus, Phys. Rev. D **63** (2001) 095005 [arXiv:hep-ph/0011233].

[11] Y. Kishimoto in "Topical Workshop on Low Radioactivity Techniques LRT 2004", AIP Conference Proceedings 785 (2005) 193

[12] S. Baek, D. G. Cerdeño, Y. G. Kim, P. Ko and C. Muñoz, JHEP **0506** (2005) 017 [arXiv:hep-ph/0505019]; D. G. Cerdeño and C. Muñoz, JHEP **0410** (2004) 015 [arXiv:hep-ph/0405057].

[13] L. Roszkowski, R. R. de Austri and R. Trotta, arXiv:0705.2012.

[14] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D **64** (2001) 035002 [arXiv:hep-ph/0012100].

[15] G. Servant and T. M. P. Tait, Nucl. Phys. B **650** (2003) 391 [arXiv:hep-ph/0206071].

[16] H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 036005 (2002) [arXiv:hep-ph/0204342].

[17] H. C. Cheng, J. L. Feng and K. T. Matchev, Phys. Rev. Lett. **89** (2002) 211301 [arXiv:hep-ph/0207125].

[18] D. Hooper and G. D. Kribs, Phys. Rev. D **67**, 055003 (2003) [arXiv:hep-ph/0208261].

[19] G. Bertone, G. Servant and G. Sigl, Phys. Rev. D **68**, 044008 (2003) [arXiv:hep-ph/0211342].

[20] F. Burnell and G. D. Kribs, Phys. Rev. D **73** (2006) 015001 [arXiv:hep-ph/0509118].

[21] K. Kong and K. T. Matchev, JHEP **0601** (2006) 038 [arXiv:hep-ph/0509119].

[22] M. Kakizaki, S. Matsumoto and M. Senami, Phys. Rev. D **74** (2006) 023504 [arXiv:hep-ph/0605280].

[23] M. Kakizaki, S. Matsumoto, Y. Sato and M. Senami, Phys. Rev. D **71**, 123522 (2005) [arXiv:hep-ph/0502059].

[24] S. Matsumoto and M. Senami, Phys. Lett. B **633**, 671 (2006) [arXiv:hep-ph/0512003].

[25] I. Gogoladze and C. Macesanu, Phys. Rev. D **74** (2006) 093012 [arXiv:hep-ph/0605207].

[26] T. Flacke, D. Hooper and J. March-Russell, Phys. Rev. D **73** (2006) 095002 [Erratum-ibid. D **74** (2006) 019902] [arXiv:hep-ph/0509352].

[27] D. Hooper and G. Zaharijas, Phys. Rev. D **75** (2007) 035010 [arXiv:hep-ph/0612137].